NASA-Industry Technical Standards and Round Robin Study on the Effect of Defects Unique to PBF Additive Manufacturing (AMTR)

Completed Technology Project (2015 - 2019)

Project Introduction

This NASA-industry effort accomplishes the following:

1) Lead collaboration between NASA Centers, other government agencies, industry, academia, and voluntary census organizations (ASTM Committees E07 on Nondestructive Testing, F42 on Additive Manufacturing (AM) Technologies, and ISO Technical Committee (TC) 261) to develop national standards for NDE of aerospace materials used in NASA/aerospace applications.

2) Lead a leveraged interlaboratory study (ILS) to develop NDE for qualification and certification of AM parts.

3) Lead ASTM E07 periodic revision of flat panel polymer matrix composite (PMC) standards: ASTM E2533 (Guide) [1], E2580 (ultrasonic testing (UT)) [2], E2581 (shearography) [3], E2582 (flash thermography) [4], E2661 (acoustic emission) [5], and E2662 (radiographic testing (RT)).

4) Lead periodic revision of composite overwrapped pressure vessel (COPV) standards: E2981 (overwrap) [6] and ASTM E2982 (liner) [7].

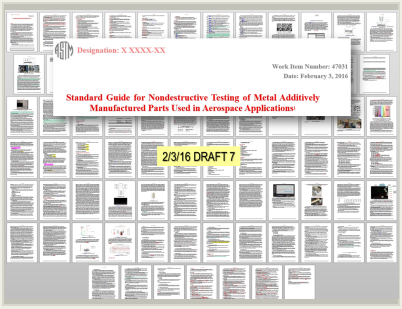
5) Develop draft NDE of AM Standard Guide (ASTM WK47031) [8], and draft In-Situ Monitoring AM Standard Guide (ASTM WK62181) [9].

6) Develop a new eddy current test (ECT)-UT-profilometer standard practice or test method for fracture control of metal parts using 90/95 Probability of Detection (POD) of critical initial flaws sizes in metal parts (TBD).

7) Respond to NASA Office of Safety and Mission Assurance (OSMA) and NASA Space Technology Mission Directorate (STMD) requests as needed (e.g., AM, advanced manufacturing, counterfeit parts, NASA/ESA/JAXA trilateral collaboration, welding and brazing standards, OSMA NDE Program publicity).

The historical standards development time line (Items 3 through 6) is shown in **Figure 1**. The WK47031 effort (Item 5) constitutes the bulk of the present focus and capitalizes on momentum created by the release of the FY14 *Nondestructive Evaluation of Additive Manufacturing State-of-the-Discipline Report* (NASA-TM-218560) [10]. The ultimate goal vis-à-vis WK47031 is to determine the effect-of-defect of specific seeded flaw types while determining detection thresholds using controlled embedded features. A portion of this effort also dovetails with the NASA Engineering and Safety Center (NESC) Universal ECT-UT-Profilometer Scanner project.

Background: One of the main obstacles slowing the acceptance and use of advanced materials (e.g., PMCs, COPVs and AM parts) in NASA and commercial space applications is the lack of a broadly accepted materials and process quality systems, including sensitive NDE procedures with well-defined accept-reject criteria. Matching VCO standards are also needed to ensure process and equipment control, finished part quality and consistent inspection



NASA-industry draft national voluntary consensus standard for nondestructive evaluation of additive manufactured parts used in aerospace applications. Credit: ASTM/Various

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methodologies for finished parts after manufacturing and after installation of parts in service. In AM, the possibility to 'design to constraint' offers a paradigm shift opening the door to make parts with shorter production lead times, less waste, improved cost, maximized properties, and reduced weight. However, to fully realize the merits of this and other advanced processing technologies, and to ensure parts of the highest quality end up in NASA/aerospace applications, new approaches to for in-situ monitoring NDE used during manufacturing, post-process NDE used on as-build and finished parts are needed. In AM, for example, NDE procedures must be able to detect flaw types (**Figure 2**), many of which are not found in cast, wrought or conventionally welded parts (**Figure 3**). Deeply embedded porosity, complex part geometry, and intricate internal features (e.g., lattice structures) impose additional challenges on conventional NDE.

Technical Approach: In the WK47031 effort (**Figure 4**), a NASA-led interlaboratory study (ILS) is currently being conducted to identify and refine NDE for inspection of AM aerospace parts. This effort is spread across government, industry, academia, the US, Europe, and Japan. A variety of promising NDE methods are being survey such as in-situ infrared thermography, computed tomography, process controlled resonance testing, neutron radiography and structured light metrology. The draft ASTM Guide will be balloted and approved using the ASTM voluntary consensus approval process. A key component will be NASA peer review, in addition to ASTM member-based and industry-focused peer review. The AM processes being examined are Powder Bed Fusion (includes Direct Metal Laser Sintering (DMLS), Selective Laser Melting (SLM) and Electron Beam Melting (EBM)); and Direct Energy Deposition (includes Electron Beam Free Form Fabrication (EBF^3)). Development of NDE and AM parts best practices through ASTM Committees F42 and E07 will be accomplished during biannually-scheduled ASTM committee week meeting and coordinated with related ISO TC 261 effort. Ongoing revision of flat panel PMC standards will be accomplished as needed (approximately every five years for each standard). New, technology-driven NDE standards will be registered and developed as needed.

Customers: NASA OSMA, NASA STMD, NESC, NASA Technical Standards Program Office, NASA Space Launch System (SLS), commercial crew, international space station, commercial space partners, NASA Materials & Processes steering committee, America Makes (formerly the National Additive Manufacturing Innovation Institute (NAMII)), Defense-Wide Manufacturing Science & Technology (DMS&T) Program, National Center for Defense Manufacturing and Machining (NCDMM).

Specific Products: ASTM E07-F42/ISO TC 261 NDE of AM Parts VCO

Organizational Responsibility

Responsible Mission Directorate:

Office of Safety and Mission Assurance (OSMA)

Lead Center / Facility:

White Sands Test Facility (WSTF)

Responsible Program:

Nondestructive Evaluation Program

Project Management

Program Director:

Terrence W Wilcutt

Program Managers:

Jeannette F Plante
Jason P Moore
Eric R Burke

Project Manager:

Charles T Nichols

Principal Investigator:

Jess M Waller

standard(s), ILS NDE of AM data, AM seeded flaw techniques, consensus NDE procedures with established precision and bias for qualification and certification of PMC, COPV and AM aerospace hardware, new NDE methods (focusing on PCRT and mCT) for characterizing unique laser PBF flaws (LOF, trapped powder, skipped layers), effect-of-defect data on sacrificial test coupons with seeded AM defects, new VCO standard guidance for seeding AM flaws and NDE detection of AM flaw types, a more detailed AM defects catalogue; an NDE section in a NASA Guide for the use of AM parts in flight oxygen systems.

Milestones:

Part 1: Finish drafting of the NDE of AM aerospace parts standard and initiate balloting prior to approval and adoption. Continue 5-year revisions of existing PMC and COPV standards.

Part 2: Fabricate AM physical reference standards and use them to demonstrate and quantify NDE (e.g., CT, PT, PCRT, RT and UT) capability as a function of materials and processing (M&P) variables. Distribute for NASA and non-NASA round-robin testing.

Part 3: Using mature M&P processes, fabricate sacrificial defect standards with known loadings of specific flaw types to determine effect-of-defect, coupled with determination of NDE detection thresholds. Distribute for NASA and non-NASA round-robin testing.

Part 4: Use NASA-industry collaboration to promote, develop and advance NASA's and industry's core NDE capabilities.

Part 5: Based on NDE findings, Evolve certification and qualification criteria for acceptance of PMC, COPV and AM aerospace parts.

Project Manager

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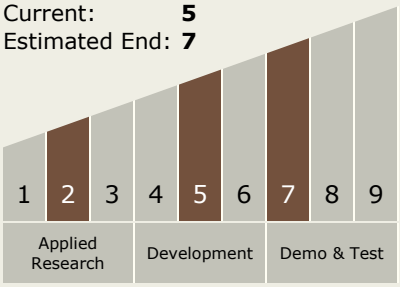
Technology Maturity (TRL)

Start: **2**
Current: **5**
Estimated End: **7**



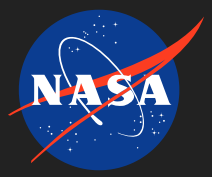
Technology Areas

Primary:

- TX12 Materials, Structures, Mechanical Systems, and Manufacturing
  - TX12.4 Manufacturing
    - TX12.4.5 Nondestructive Evaluation and Sensors

Target Destination

Foundational Knowledge



Project Leader

Jess M. Waller

(575) 524-5249

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References:

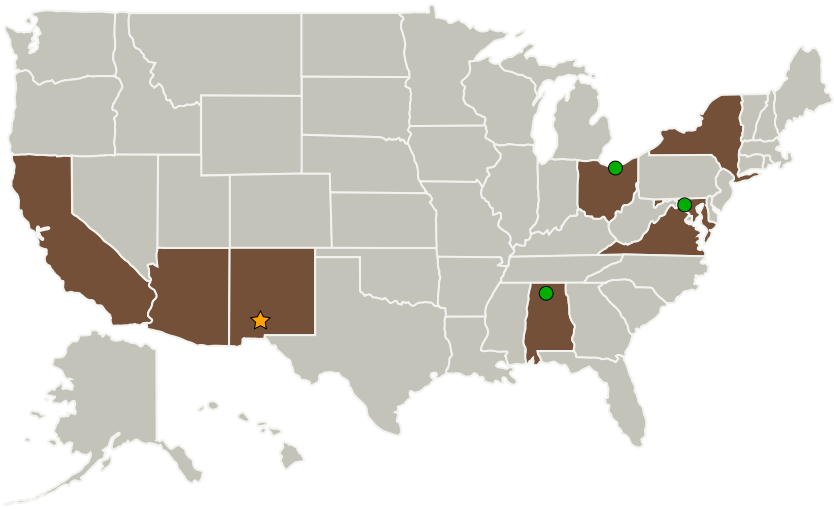
2. ASTM E2580-07, -12 Standard Practice for Ultrasonic Testing of Flat Panel Composites and Sandwich Core Materials Used in Aerospace Applications, Annual Book of ASTM Standards.
3. ASTM E2581-07, -14 Standard Practice for Shearography of Polymer Matrix Composites and Sandwich Core Materials in Aerospace Applications, Annual Book of ASTM Standards.
4. ASTM E2582-07, -07(2014) Standard Practice for Infrared Flash Thermography of Composite Panels and Repair Patches Used in Aerospace Applications, Annual Book of ASTM Standards.
5. ASTM E2661-10, -15 Standard Practice for Acoustic Emission Qualification of Plate-like and Flat Panel Composites Used in Aerospace Applications, Annual Book of ASTM Standards.
6. ASTM E2662-09, -15 Standard Practice for Radiologic Testing of Flat Panel Composites and Sandwich Core Materials Used in Aerospace Applications, Annual Book of ASTM Standards.
7. ASTM E2981-15 Standard Guide for Nondestructive Testing of Composite Overwraps in Filament Wound Pressure Vessels Used in Aerospace Applications, Annual Book of ASTM Standards.
8. ASTM E2982-14 Standard Guide for Nondestructive Testing of Metallic Thin-Walled Liners in Filament Wound Pressure Vessels Used in Aerospace Applications, Annual Book of ASTM Standards.
9. ASTM WK47031, new Draft Standard – Guide for Nondestructive Testing of Metal Additive Manufactured Parts Used in Aerospace Applications.
10. Waller, J. M., Parker, Bradford H., Hodges, Kenneth, L., Burke, Eric R., Walker, James, L., Nondestructive Evaluation of Additive Manufacturing State-of-the-Discipline Report, NASA/TM—2014–218560, November 2014.

Anticipated Benefits

Materials test data generated and shared collaboratively in support of an ASTM Round Robin Study led by NASA. In addition, NDE procedures are refined and tailored for additive manufactured parts, focusing on metal Laser-Powder Bed Fusion (L-PBF) parts. The improved procedures are then promulgated in national voluntary consensus standards. In addition to round robin testing and standards, progress is also made in the following areas: 1) NASA/ESA/JAXA collaboration in NDE (CT, UT, RT, PCRT) performed on AM physical reference standards and representative spaceflight hardware, 2) adopting uniform AM parts categories between NASA/ESA/JAXA, and 3) adopting harmonized

international AM defect terminology.

Primary U.S. Work Locations and Key Partners



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Organizations Performing Work	Role	Type	Location
★White Sands Test Facility(WSTF)	Lead Organization	NASA Facility	Las Cruces, New Mexico
Air Force(USAF)	Supporting Organization	US Government	Washington, District of Columbia
America Makes	Supporting Organization	Industry	
American National Standards Institute(ANSI)	Supporting Organization	Industry	New York, New York
Department of Defense(DoD)	Supporting Organization	US Government	Washington, District of Columbia
Federal Aviation Administration(FAA)	Supporting Organization	US Government	Washington, District of Columbia
●Glenn Research Center(GRC)	Supporting Organization	NASA Center	Cleveland, Ohio
●Goddard Space Flight Center(GSFC)	Supporting Organization	NASA Center	Greenbelt, Maryland
Johns Hopkins University Applied Physics Laboratory(JHU/APL)	Supporting Organization	R&D Center	Laurel, Maryland
●Marshall Space Flight Center(MSFC)	Supporting Organization	NASA Center	Huntsville, Alabama
National Institute of Standards and Technology(NIST)	Supporting Organization	US Government	Boulder, Colorado
Pennsylvania State University-Main Campus(Penn State)	Supporting Organization	Academia	University Park, Pennsylvania

Co-Funding Partners	Type	Location
Aerojet Rocketdyne Holdings, Inc.	Industry	El Segundo, California
ASTM International(ASTM)	Industry	West Conshohocken, Pennsylvania
Australian Nuclear Science and Technology Organisation(ANSTO)	International	Lucas Heights, Outside the United States, Australia
CalRAM Inc	Industry	
Concept Laser GmbH	Industry	Lichtenfels
European Space Agency(ESA)	International	Paris, Outside the United States, France
GE Aviation	Industry	Cincinnati, Ohio
Honeywell Aerospace	Industry	
Incodema3D	Industry	Freeville, New York
International Organization for Standardization(ISO)	Industry	Geneva, Outside the United States, Switzerland
Japan Aerospace Exploration Agency(JAXA)	International	Sagamihara, Outside the United States, Japan
Lockheed Martin Space Systems(LMSS)	Industry	Sunnyvale, California
Los Alamos National Laboratory(LANL)	R&D Center	Los Alamos, New Mexico
Northrop Grumman Aerospace Systems(NGAS)	Industry	Redondo Beach, California
Southern Research Institute	Academia	Birmingham, Alabama
SpaceX	Industry	
Stellenbosch University	Academia	Stellenbosch, Outside the United States, South Africa
The Boeing Company(Boeing)	Industry	Chicago, Illinois
UTC Aerospace Systems(UTAS)	Industry	Connecticut
Vibrant Corporation	Industry	Albuquerque, New Mexico

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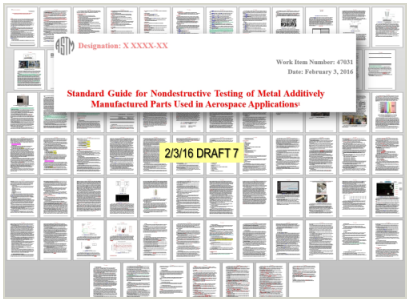
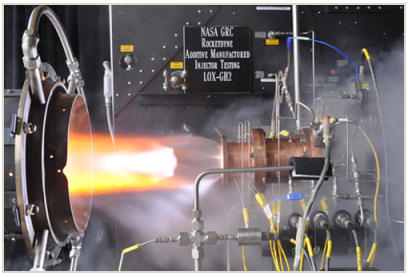
Primary U.S. Work Locations	
Alabama	Arizona
California	Maryland
New Mexico	New York
Ohio	Virginia
Outside the United States	

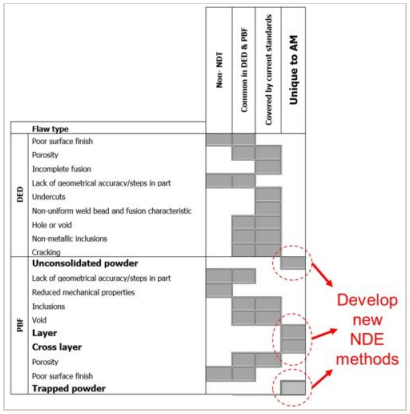
Images



AM NDE Standard
NASA-industry draft national voluntary consensus standard for nondestructive evaluation of additive manufactured parts used in aerospace applications. Credit: ASTM/Various *(https://techport.nasa.gov/image/20729)*



AM Thruster
Additively manufactured LOX-GH2 thruster, one of many components for which new NDE standards are required for certification. Credit: NASA GRC/Rocketdyne *(https://techport.nasa.gov/image/20726)*



AM-specific Defect Classifications
Nondestructive evaluation development areas for additive manufacturing (AM) laser directed energy deposition (DED), and laser powder bed fusion (PBF) defect types. Credit: ISO TC 261 *(https://techport.nasa.gov/image/20728)*

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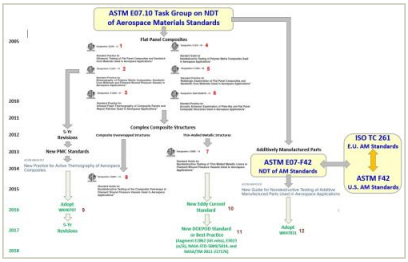
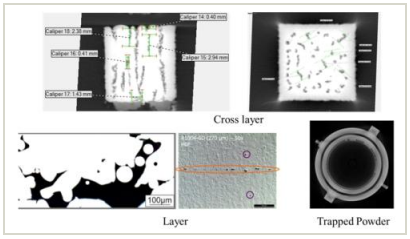
NASA OSMA's commitment to VCO standards is acknowledged
ASTM/SES Robert J. Painter Award for Meritorious Service
(https://techport.nasa.gov/image/20731)



Standards Supported
NASA-led national voluntary consensus standards development activities. NASA directed NDE-discipline subteams during standards development.
(https://techport.nasa.gov/image/20730)



Typical PBF AM Defects
Typical power bed fusion defects. Credit: NASA
(https://techport.nasa.gov/image/20727)

Stories

NASA's Dr. Jess Waller Receives ASTM/SES Painter Award for Work on Nondestructive Testing Standards
(https://techport.nasa.gov/file/29424)

Links

Evaluation of Additively Manufactured Metals for Use in Oxygen Systems, News Article, OSMA, August 23, 2016
(https://sma.nasa.gov/news/articles/newsitem/2016/08/23/evaluation-of-additively-manufactured-metals-for-use-in-oxygen-systems)

NASA Collaborates to Progress AM Efforts Both Nationally and Internationally, News Article, OSMA, October 13, 2016
(https://sma.nasa.gov/news/articles/newsitem/2016/10/13/nasa-collaborates-to-progress-am-efforts-both-nationally-and-internationa)

OSMA's NDE Program Published Capabilities Data Book, News Article, OSMA, January 25, 2016
(https://sma.nasa.gov/news/articles/newsitem/2016/01/25/osma-s-nde-program-published-capabilities-data-book)

TechPort Approval for Public Release
(https://daa.jsc.nasa.gov/showrecord.cfm?ControlNo=35732)

Project Website:

https://sma.nasa.gov/news/articles?taxonomy=topics&propertyName=Disciplines&taxon=nondestructive-evaluation